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Canada Centre for Mineral and Energy Technology

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Metals Technology Laboratories

Laboratoires de la technologie des métaux

Canada

FULL SCALE PIPE BENDING TEST

PHASE I: FEASIBILITY STUDY (PERD)

FINAL REPORT

BY

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ABSTRACT

Full-scale pipe bending tests are proposed for the Mackenzie Valley pipeline. These will require internal pressure combined with pure bending to determine allowable buckling strains. A testing facility located at The Welding Institute of Canada, Oakville, Ontario, may be used for this work. A comprehensive assessment of the facility found the following:

1. The present facility does not have the load capacity required for the proposed work.
2. The load reaction frame is capable of resisting the required loading with a factor of safety of 1.3 based on yield.
3. The facility is not equipped with a pressure system for pressurizing the pipe.
4. The control system and data acquisition system need to be upgraded to meet the requirements of the proposed program.
5. The cost for refurbishment of the facility is estimated to be $140,000.00, and 60 to 90 days are required to carry out the necessary modifications.
6. The cost per test is estimated to be $35,000.00 and time for completion, 30 to 45 days.

RÉSUMÉ

On envisage d'effectuer des essais de flexion en grandeur réelle pour le pipeline de la vallée du Mackenzie. Ces essais permettront de déterminer la déformation de flambage sous l'effet combiné d'une pression interne et de la flexion pure. Un banc d'essai situé à l'Institut de Soudage du Canada à Oakville en Ontario pourrait être utilisé pour ce programme. Une évaluation détaillée des facilités a permis de trouver que:

1. Le banc d'essai ne peut pas actuellement atteindre la charge requise pour le travail proposé.
2. Le bâti est capable de supporter la charge requise avec un facteur de sécurité de 1.3 basé sur la limite élastique.
3. Il n'y a pas de système de pressurisation pour le tube.
4. Les systèmes de contrôle et d'acqisition des données doivent être améliorés pour satisfaire aux exigences du programme.
5. Le coût de rénovation des facilités devrait atteindre 140000 $, et de 60 à 90 jours seraient nécessaires pour effectuer les modifications requises.
6. Un essai devrait coûter environ 35000 $, et son achèvement devrait prendre de 30 à 45 jours.

1.0 INTRODUCTION

MDT Engineering Ltd has received a DSS Contract (23440-0-9132/01-SQ) to provide a feasibility study on full-scale pipe bending tests using the facilities located at the Welding Institute of Canada, (WIC), Oakville, Ontario. The work to be completed under this contract is covered by the following statement of work:

- Establish the limits of WIC's facilities
- Propose modifications to existing facilities to meet the requirements of the proposed program, including pipe pressure generation and control
- Examine safety considerations, particularly with respect to the use of internal pressure
- Examine equipment requirements to fully computerize test control and data acquisition
- Provide approximately the estimates of costs and time required to complete all the modifications deemed necessary
- Provide rough estimates of the cost of running a full-scale test

This report covers all of the above work statements and is submitted in accordance with the contractual requirements issued by DSS.

2.0 BACKGROUND

The Beaufort Gas Project which is scheduled for start-up in 1998, at the earliest, is expected to use a 914 mm (36") diameter pipeline which is to be located along the east side of the Mackenzie River. This pipeline will be exposed to severe frost heave conditions which need to be controlled to meet the allowable pipe strains.

Data used to determine allowable strain levels exhibit a great deal of variability and therefore it is hoped that further research and testing will reduce the conservatism in pipeline design and define more realistic factors of safety. Of particular interest is the effect of pipe diameter/thickness ratio on buckling strain, therefore D/t ratios ranging from 30 to 60 and pipe strengths from 414 MPa (60 kpsi) to 552 MPa (80 kpsi) are to be investigated in full-scale pipe bending tests. It is also understood that the envisaged test program will require an internal pressure to be combined with the bending .

3.0 EVALUATION OF THE WIC FACILITIES

Figure 1 is a simplified schematic diagram of the pipe testing facility located at the Welding Institute of Canada (WIC), Oakville, Ontario. The loading frame is 12.2 m (40') long and in its present configuration twenty 445 kN (100,000 lb) hydraulic jacks, evenly spaced along its length, load the pipe section under test. Neoprene lined fabricated steel saddles distribute the discrete jack loads over semicircular areas to simulate ground heave loading. 50.8 mm (2") thick steel bulkheads welded to the ends of the pipe section are attached with ten, 50.8 mm (2") diameter tie rods to the loading frame and transmit the pipe reaction forces in the form of a simple end restraint. Access holes in the bulkheads allow instrumentation such as strain gauges and thermocouples to be placed inside the test specimen. A system made up of steel cables and energy dissipation devices absorbs the energy of the fractured components to provide a safe testing environment.

An Enerpac model PER-5035, 68.95 MPa (10,000 psi) hydraulic power pack is the primary pressure source for the facility. Pressure is

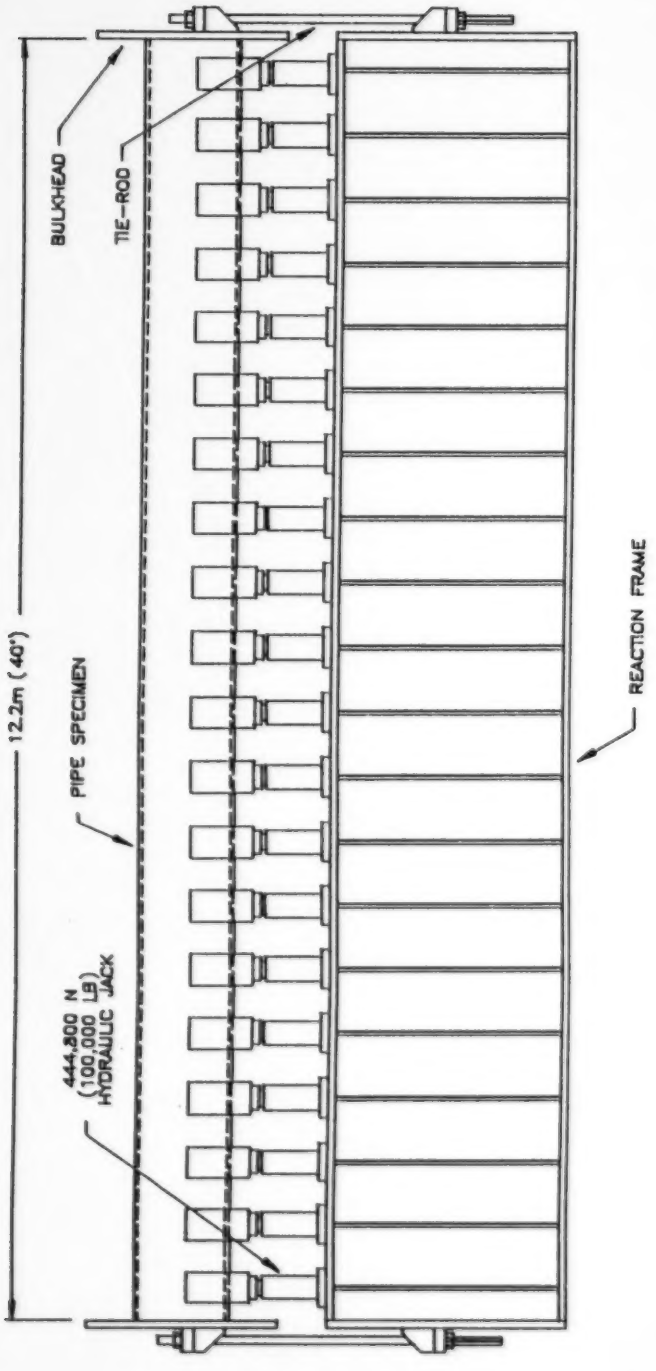

BULKHEAD
TIE-ROD
12.2m (40')
PIPE SPECIMEN
444,800 N
(100,000 LB)
HYDRAULIC JACK
REACTION FRAME

Figure 1

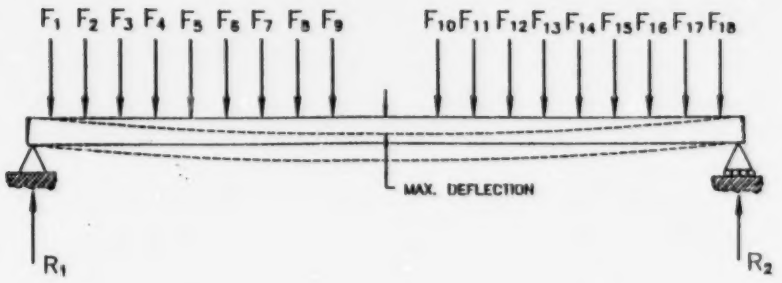
regulated and controlled with a closed loop system comprising an MTS Model 406.11A servo controller, a 0-34.5 MPa (0-5000 psi) pressure transducer, and Moog Model A 076-233, 34.5 MPa (5000 psi) servovalve. With a maximum jack pressure of 68.95 MPa (10,000 psi) the testing facility is capable of generating a pipe bending moment of 13.56×10^6 N-m (120×10^6 in-lb) with a loading frame deflection of 15.24 mm (0.6"). However since the Moog servovalve has a maximum pressure rating of 34.5 MPa (5000 psi), in its present form the testing facility's capacity is limited to 6.78×10^6 N-m (60×10^6 in-lb).

4.0 GENERAL REQUIREMENTS FOR PROPOSED PROGRAM

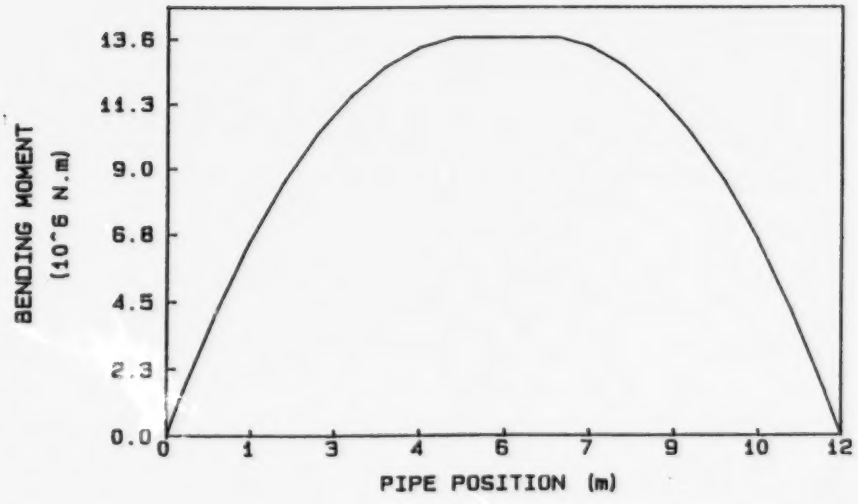
The local buckling (wrinkling) of tubular members is governed by diameter to wall thickness ratio D/t, and is affected by local load concentrations, degree of restraint, applied pressure, residual stresses and various other factors. To obtain meaningful test data in a laboratory environment, the loading fixture used must provide an appropriate unrestrained test section where the buckling should occur. This naturally requires a smooth, gradual transition from a low stress at areas remote from the test section to the critical buckling stress at the test section.

4.1 Load Distribution

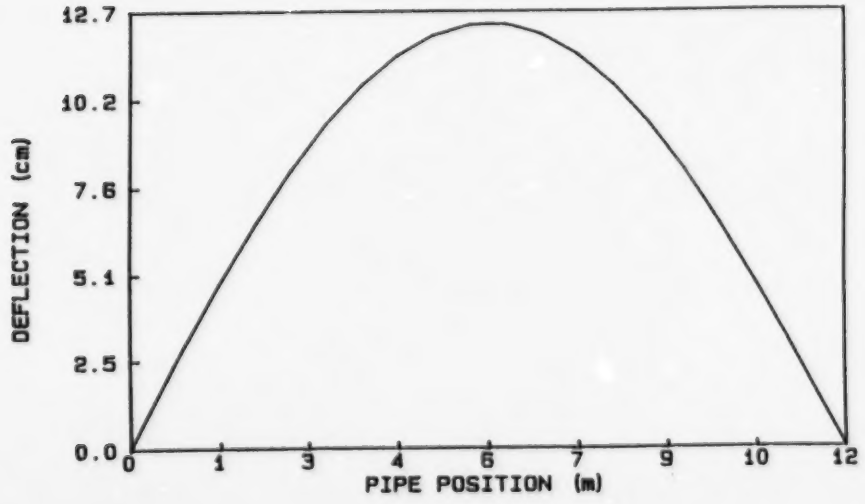
The diagram presented as Figure 2a shows the load distribution achievable with WIC's loading frame in its current configuration; with the two central jack loads removed to produce the unrestrained pure moment test section required. The advantages of this type of loading are twofold; the loads are evenly distributed over a large section of the pipe unlike the severe local loading typical of four point bend


F1 F2 F3 F4 F5 F6 F7 F8 F9
F10 F11 F12 F13 F14 F15 F16 F17 F18
MAX. DEFLECTION
R1
R2

(a)


BENDING MOMENT
(10^6 N.m)
13.6
11.3
9.0
6.8
4.5
2.3
0.0
0
1
3
4
6
7
9
10
12
PIPE POSITION (m)

(b)


DEFLECTION (cm)
12.7
10.2
7.6
5.1
2.5
0.0
0
1
3
4
6
7
9
10
12
PIPE POSITION (m)

(c)

Figure 2

tests, and low moment (stress) sections exist where specimen attachment girth welds may be placed.

4.2 Load Capacity

The elastic-plastic analysis for 552 MPa (80 kpsi) steel presented in Appendix A shows that the fully plastic moment for 32 mm (1 1/4") pipe, the thickest to be tested as part of the proposed program, is 13.56 x 10^6 N-m (120.8 x 10^6 in-lb). This is shown in the moment diagram presented as Figure 2b. To achieve this moment with the load distribution shown in Figure 2a individual jack loads of 552 kN (124,000 lb) are required. Therefore considering the 34.5 MPa (5,000 psi) pressure limitation and corresponding 223 kN (50,000 lb) load limit per jack of the WIC facility, the total number of loading jacks will need to be increased.

4.3 Stroke Capacity

An elastic deflection analysis for the 32 mm (1 1/4") wall pipe is also included in Appendix A. The results for the case of the fully plastic applied moment presented as Figure 2c show a maximum mid-span deflection of approximately 123.3 mm (4.856"). A similar mid-span deflection was also computed for the 16 mm (5/8") wall pipe. Actual deflections, which take into consideration plasticity and/or buckling, are expected to be significantly larger. However the 330 mm (13") stroke available with WIC's loading jacks should be able to accommodate the fully developed buckling condition combined with the 15.8 mm (0.623") loading frame deformation.

4.4 Pressure Containment

For safety considerations, water should be used to pressurize the pipe, particularly since on completion of a test the specimen has to be flame cut to remove it from the test rig. To contain this pressure two hemispherical end closures can be welded to the pipe test section to create a totally self reacting system, and pipe extensions welded to these end closures can provide non-pressurized sections for attachment to the loading frame bulkheads. The scheme proposed is presented in more detail later.

4.5 Control & Instrumentation

Local buckling is an instability which offers few signs or warnings to indicate the final collapse condition. Therefore to obtain buckling data with a minimum of scatter, strain data should be sampled at small load increments, particularly as the buckling state is approached. This is best accomplished with computer control. A computer controlled multi-channel servo-controlled testing system capable of interfacing with data acquisition systems and controlling sampling rates is therefore required for the proposed program. The multi-channel control is particularly important since the effect of pressure variation on buckling may also need to be investigated.

4.6 Safety

The proposed buckling tests are to be carried out at room temperature and therefore the probability of pipe fracture is extremely low. However in the event of an unexpected fracture the safety restraint systems with which WIC's loading frame is fitted can accommodate the transverse energy release, and the longitudinal energy release due to

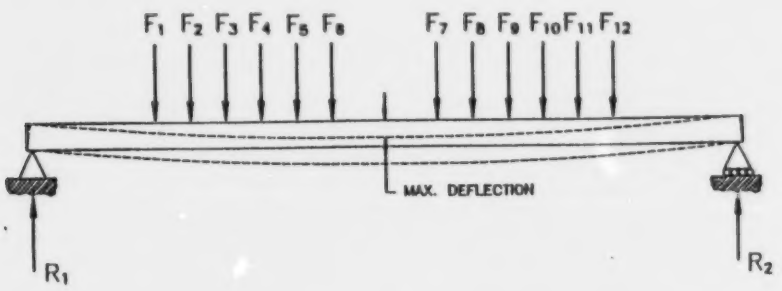
the internal pressure can be absorbed by the bulkhead tie rods. Nevertheless, to enhance the overall safety of the testing facility it is recommended that all permanent welds and pressure containment details meet ASME Pressure Vessel Code requirements. In addition, water containment systems such as trays under the pipe and splash guards should be installed, and all test control and data acquisition systems should be remote and protected from the testing environment.

5.0 REFURBISHMENT OF WIC'S FACILITIES

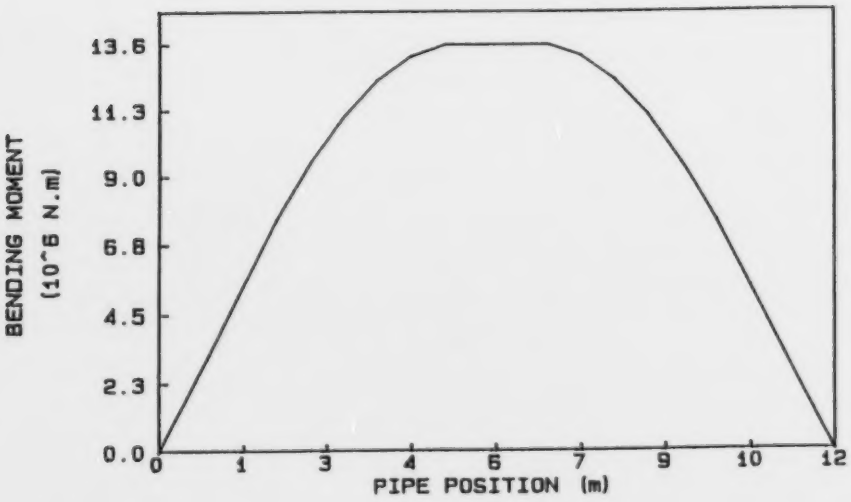
5.1 Loading Frame

The analysis of Appendix A shows that at the maximum anticipated load the loading frame has a factor of safety of 1.3 based on yield. This should be adequate for the proposed testing program. However since the individual loading stations are currently limited to 223 kN (50,000 lb) based on the 34.5 MPa (5,000 psi) pressure available, more jacks will be required to bring the facility up to the necessary load capacity.

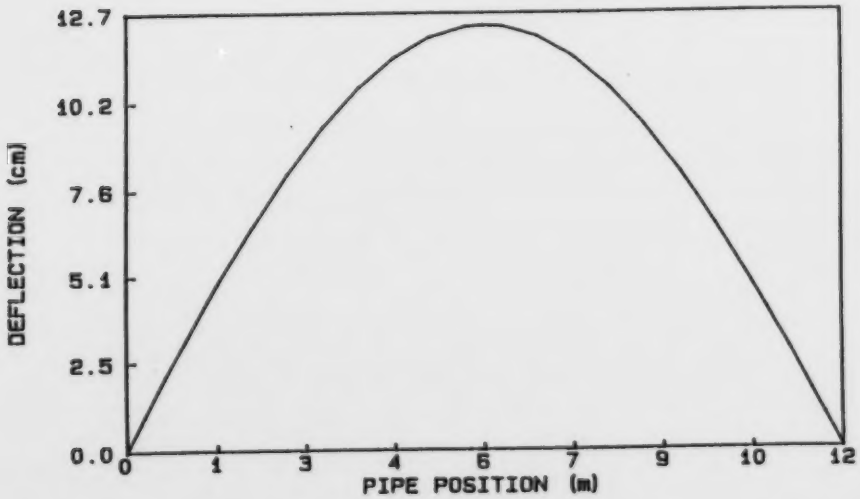
To use the loading jacks more efficiently it is recommended that the pipe load distribution presented as Figure 3a be adopted. An analysis for this can be found in Appendix B. The moment and displacement distributions, Figures 3b and 3c respectively, are similar to those of Figures 2b and 2c, however displacements are more concentrated toward the test section which is advantageous in that it tends to reduce the probability of having unwanted buckling failures in sections of the pipe other than the test section. To achieve the required pipe moment using this approach, stations 1,2,11 and 12 need to be fitted with two jacks each, and stations 3 to 10 with three jacks each. Since the WIC facility only has 20 jacks, 12 additional ones are required.


F1 F2 F3 F4 F5 F6
F7 F8 F9 F10 F11 F12
MAX. DEFLECTION
R1
R2

(a)


BENDING MOMENT
(10^6 N.m)
13.6
11.3
9.0
6.8
4.5
2.3
0.0
0
1
3
4
6
7
9
10
12
PIPE POSITION (m)

(b)


DEFLECTION (cm)
12.7
10.2
7.6
5.1
2.5
0.0
0
1
3
4
6
7
9
10
12
PIPE POSITION (m)

(c)

Figure 3

Figure 4 is a simplified representation of the WIC loading frame reconfigured for the proposed testing program. The hemispherical pressure containment end closures and associated pipe sections shown remain permanently attached to the bulkheads, and the pipe specimen is held in place with the installation girth welds identified. Following a test, the specimen is removed by flame cutting the transition section as close as possible to the installation weld. The transition section can then be dressed in preparation for the installation of a new somewhat longer specimen.

Figure 5 shows the typical multiple jack saddle arrangement proposed for the loading frame. To incorporate this, additional web plate stiffeners and corresponding bearing plates need to be added to the saddles and loading frame respectively. Also, to distribute the saddle loads more evenly when the pipe is in its deformed state the simple swivel joint detail also shown in Figure 5 should incorporated. This helps to prevent unwanted buckling that may be produced by local saddle load concentrations due to a saddle-pipe slope mismatch.

5.2 Pressure Supply And Control

The pressure source used for loading the hydraulic jacks of WIC's loading frame is adequate for the proposed testing facility. However since an additional pressure source is required for pressurizing the test pipe with water, it is recommended that one larger unit be purchased to serve both functions. This system should have a capacity of 7.6 to 18.9 liters per minute (2 to 5 GPM) with a maximum operating pressure of 34.5 MPa (5,000 psi). Load control can be achieved as before using a pressure controlled feedback loop, while water pressure

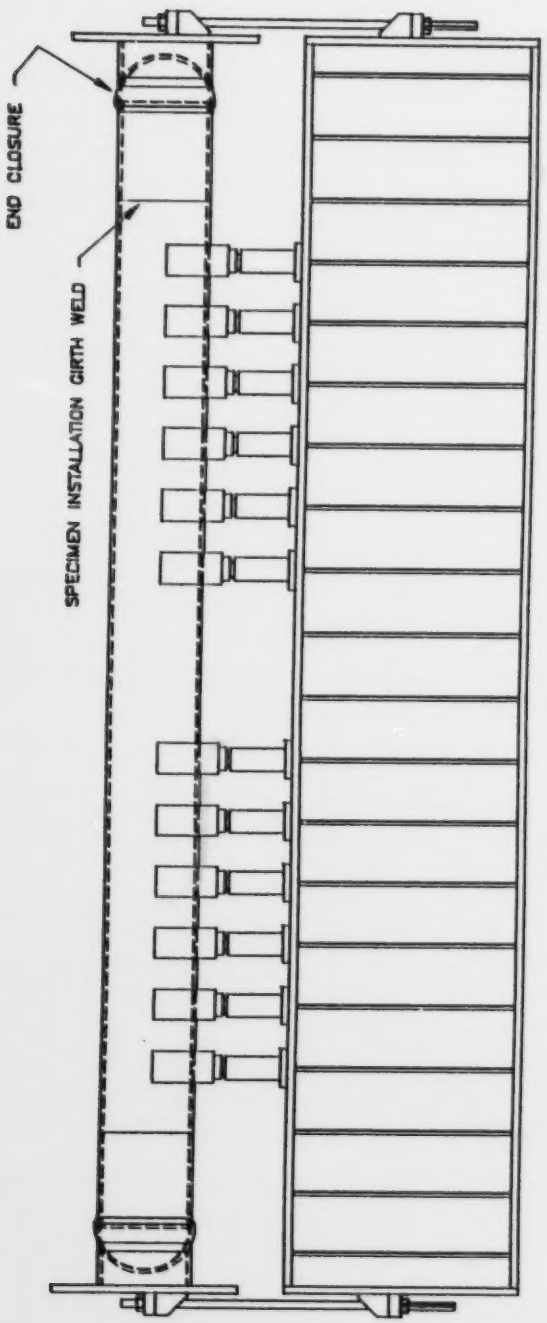


Figure 4

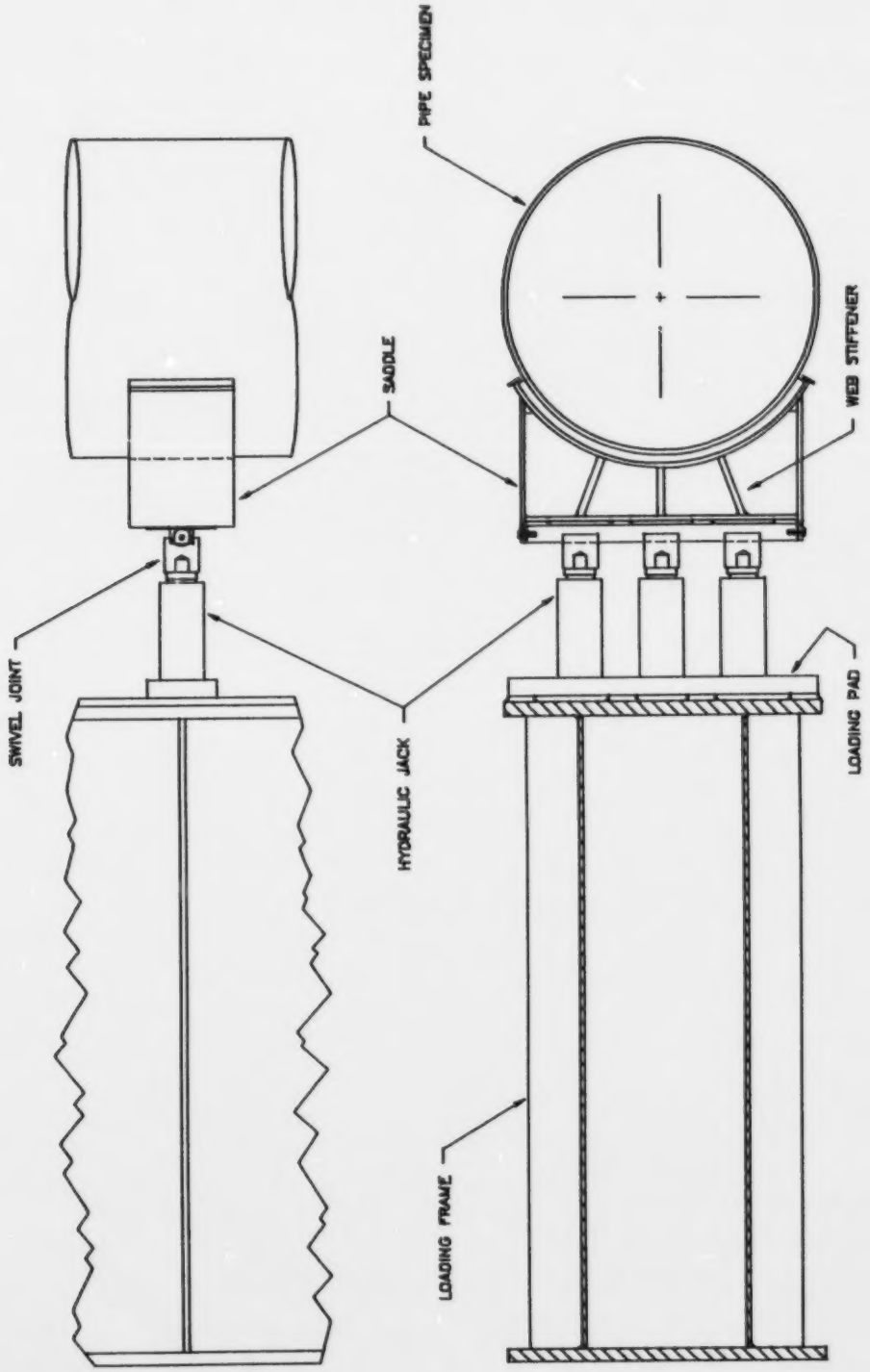

PIPE SPECIMEN
SADDLE
WEB STIFFENER
SWIVEL JOINT
HYDRAULIC JACK
LOADING PAD
LOADING FRAME

Figure 5

should be controlled using a second feedback loop with a transfer barrier accumulator to separate the primary medium, oil, from the secondary medium, water. The pressure source should also be equipped with a 345 kPa (50 psi) water pump to circulate the heat exchanger water from WIC's water storage tank, and to prepressurize the test pipe to reduce the volume of entraped air. The latter is essential due to the transfer barrier accumulator's finite capacity 75.7 liter (20 gal US). The water volume displacement calculations on which the accumulator size is based may be found in Appendix B.

5.3 Test Control And Data Acquisition

For the proposed testing program both load and pressure need to be controlled independently, and be synchronized with data acquisition functions. This can be accomplished with a PC controlled testing system designed to interface with multiple servo loops. An MDT Engineering PC Test Control System, or equivalent, capable of interfacing with multi-channel strain gauge data acquisition systems such as the MDT Model M100 is therefore recommended. This allows the operator to specify both load and pressure loading rates and data acquisition sampling rates. The latter may even be changed automatically as the test progresses so that as the specimen approaches the buckling state, data may be collected at more frequent intervals.

6.0 COSTING

Details on which the anticipated program costs are based are submitted as Appendix C. Summaries of these are presented in the following subsections.

6.1 Equipment Refurbishment

The cost figures for refurbishing the WIC testing facilities are as follows:

Pressure containment system including pressure source.	$ 46,980.00
Modification of loading frame.	21,440.35
Electronic control and data acquisition.	55,500.00
Fees - Professional, technical, and administrative.	13,500.00
TOTAL	$137,420.35

6.2 Testing

The costs per test as estimated by WIC are as follows:

Professional Fees	$ 7,068.80
Technician Fees	22,791.00
Consumables	4,600.00
NDE	600.00
TOTAL	$35,059.80

7.0 TIMING

It is estimated that the time required for refurbishment of WIC's facilities is 60 to 90 days. This is based on availability of skilled personnel and component delivery times. The time required for each buckling test is expected to be 30 to 45 days, although this may be reduced pending the availability of additional personnel.

8.0 FEASIBILITY AND COST ESTIMATE FOR UPGRADING WIC'S FACILITIES TO ACCOMMODATE 1076 mm (42") PIPE

An analysis of the loading requirements for 38 mm (1 1/2") wall, 1067 mm (42") diameter, 483 MPa (70 kpsi) pipe is also included in Appendix B. This shows that a maximum bending moment of 19.5 x 10 N-m (172.8 x 10 in-lb) is required to fully yield the pipe test section. To achieve this load capacity the following modifications and/or additions to WIC's facilities are required:

1. The loading frame must be reinforced by welding 25 mm (1") thick cheek plates to the existing flange plates.
2. Twelve new saddle assemblies need to be fabricated.
3. 1067 mm (42") diameter pressure vessel end closures with mating pipe sections need to be fabricated and welded to the bulkhead plates.
4. The twelve new 445 kN (100,000 lb) hydraulic jacks required for the 914 mm (36") pipe tests need to be upgraded to 890 kN (200,000 lbs) and four additional 445 kN (100,000 lb) units need to be purchased.

The following additional costs have been estimated for the upgrading:

Upgrading of hydraulic jacks	$14,000.00
Fabrication of 12 saddles	9,600.00
Upgrading of pressure containment system	4,500.00
Reinforcement of loading frame	22,000.00
Total Additional Costs	$50,100.00

The total estimated cost for a 1067 mm (42") pipe testing facility is therefore approximately $190,000.00. The cost per test is expected to be the same as for the 914 mm (36") pipe.

9.0 CONCLUSIONS AND RECOMMENDATIONS

Analysis has shown that the pipe testing facility at The Welding Institute of Canada can be used for the tests proposed for the Beaufort Project. However the following changes are required:

1. The load capacity must be increased.
2. A pressure containment system must be incorporated.
3. The control and data acquisition systems must be upgraded.

The cost for this refurbishment is estimated to be approximately $140,000.00 and $190,000.00 for 914 mm (36") and 1067 mm (42") pipes respectively, and the time for completion is expected to be 60 to 90 days.

To test and evaluate all aspects of the proposed refurbishment, establish the best testing procedure, and to firm up the cost and time requirements for testing which are currently estimated to be $35,000.00 and 30 to 45 days respectively, it is recommended that one or two commissioning tests be performed as part of the next phase of the proposed program.

APPENDIX A

ANALYSIS OF WIC'S EXISTING FACILITY

MOMENT OF INERTIA

REACTION GIRDER (REF. DWG D1131-2)

$Ixx=1/12(b1*h1^3-b2*h2^3)$

where, b1=32 in
h1=75 in
b2=31 in
h2=72 in

Ixx=160776 in^4

TEST PIPE d=36, t=1.25 in, d/t=30

$Ixx=1/4*pi(r2^4-r1^4)$

where, r1=d/2-t
r1=16.75 in
r2=d/2
r2=18 in

Ixx=20625 in^4

TEST PIPE d=36, t=0.625 in, d/t=60

where, r1=17.375 in
r2=18 in

Ixx=10868 in^4

TEST PIPE YIELDING MOMENT

$My=Sy*Ixx/r2$

where, Yield Stress Sy=80000 psi

for d=36 in, t=1.25 in

My=91.67 Min.lb

for d=36 in, t=0.625 in

My=48.30 Min.lb

PLASTIC MOMENT and SHAPE FACTOR (K) Mp=K*My

K=16*r2(r2^3-r1^3)/(3*pi*(r2^4-r1^4))

for d=36 in, t=1.25 in

K=1.318

Mp=1.318*91.67

Mp=120.8 Min.lb

for d=36 in, t=0.625 in

K=1.295

Mp=1.295*48.30

Mp=62.58 Min.lb

SAFETY FACTOR FOR REACTION GIRDER (REF DWG D1131-2)

BENDING STRESS Sb=Mp*y/Ixx

where, Mp=120.8 Min.lb max.
y=75/2 in
Ixx=160776 in^4

Sb=27989 psi

Structural Steel Sy=36 ksi

Therefore, SAFETY FACTOR SF=Sy/Sb =1.3

REACTION GIRDER (REF. DWG D1131-2) MAX. ELASTIC DEFLECTION

MAX. DEFLECTION ymax=SUM(F*a/(24*E*1)*(3*L^2-4*a^2))

where, F= jack load (lb)
L=480 in
E=30E6 psi (Young's Modulus)
Ixx=160776 in^4
a=position of jack (in) from end of girder

for load distribution see Figure no. 1

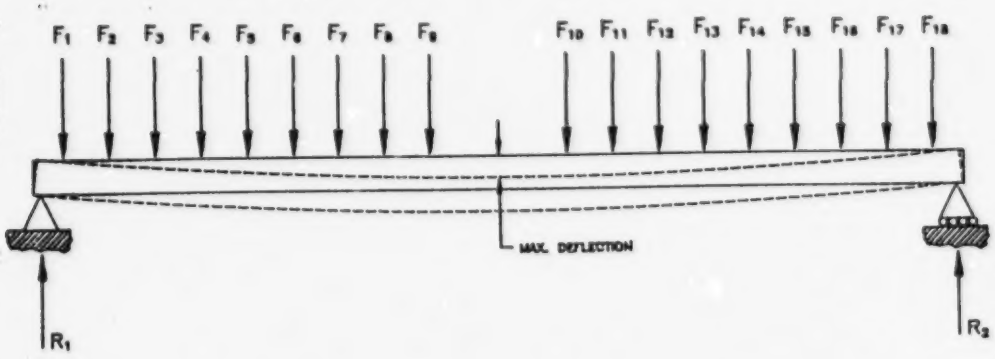


FIGURE No. 1

where, F1-F9=124,000 lb
a1=12 in
a2=36 in
a3=60 in
a4=84 in
a5=108 in
a6=132 in
a7=156 in
a8=180 in
a9=204 in

REACTION GIRDER ymax=0.623 in

EXISTING WIC PIPE BENDING RIG 18 09 90

No. of JACKS/SIDE=	9.00	PIPE d=	36.00 in
JACK CAPACITY=	124.30 Klb	PIPE t=	1.250 in
LENGTH OF PIPE=	480.00 in	Ixx=	20625 in 4
REACTION FORCE=	1118.70 Klb	YIELD S=	80000.00 psi

DETA X [ft]	QTY	POSITION [ft]	V [Klb]	M [Min.lb]	TOTAL M [Min.lb]	STRESS [ksi]	ymax [in]
0.00	0.00	0.00	1118.70	0.00	0.00	0.00	0.0000
1.00	1.00	1.00	994.40	13.42	13.42	11.72	0.0694
2.00	1.00	3.00	870.10	23.87	37.29	32.54	0.2067
2.00	1.00	5.00	745.80	20.88	58.17	50.77	0.3399
2.00	1.00	7.00	621.50	17.90	76.07	66.39	0.4661
2.00	1.00	9.00	497.20	14.92	90.99	79.41	0.5827
2.00	1.00	11.00	372.90	11.93	102.92	89.82	0.6867
2.00	1.00	13.00	248.60	8.95	111.87	97.63	0.7754
2.00	1.00	15.00	124.30	5.97	117.84	102.84	0.8461
2.00	1.00	17.00	0.00	2.98	120.82	105.44	0.8960
2.00	0.00	19.00	0.00	0.00	120.82	105.44	0.0000
							4.8691

r2=	18.000	in
r1=	16.750	in
K=	1.318	SHAPE FACTOR
My=	91.667	Min.lb
Mp=	120.808	Min.lb

EXISTING WIC PIPE BENDING RIG 18 09 90

No. of JACKS/SIDE=	9.00	PIPE d=	36.00 in
JACK CAPACITY=	64.40 klb	PIPE t=	0.625 in
LENGTH OF PIPE=	480.00 in	Ixx=	10368 in 4
REACTION FORCE=	579.60 klb	YIELD S=	80000.00 psi

DETA X [ft]	QTY	POSITION [ft]	V [klb]	M [Min.lb]	TOTAL M [Min.lb]	STRESS [ksi]	ymax [in]
0.00	0.00	0.00	579.60	0.00	0.00	0.00	0.0000
1.00	1.00	1.00	515.20	6.96	6.96	11.52	0.0682
2.00	1.00	3.00	450.80	12.36	19.32	32.00	0.2032
2.00	1.00	5.00	386.40	10.82	30.14	49.92	0.3342
2.00	1.00	7.00	322.00	9.27	39.41	65.27	0.4583
2.00	1.00	9.00	257.60	7.73	47.14	78.07	0.5729
2.00	1.00	11.00	193.20	6.18	53.32	88.31	0.6752
2.00	1.00	13.00	128.80	4.64	57.96	95.99	0.7624
2.00	1.00	15.00	64.40	3.09	61.05	101.11	0.8319
2.00	1.00	17.00	0.00	1.55	62.60	103.67	0.8810
2.00	0.00	19.00	0.00	0.00	62.60	103.67	0.0000
							4.7873

r2=	18.000	in
r1=	17.375	in
K=	1.295	SHAPE FACTOR
My=	48.304	Min.lb
Mp=	62.576	Min.lb

APPENDIX B

ANALYSIS OF WIC'S

REFURBISHED FACILITY

SECTIONAL PROPERTIES AS PER APPENDIX A

REACTION GIRDER (REF. DWG D1131-2) MAX. ELASTIC DEFLECTION

MAX. DEFLECTION ymax=SUM(F*a/(24*E*I)*(3*L^2-4*a^2))

where, F= jack load (lb)
L=480 in
E=30E6 psi (Young's Modulus)
Ixx=160776 in^4
a=position of jack (in) from end of girder

for the load distribution Figure no. 2

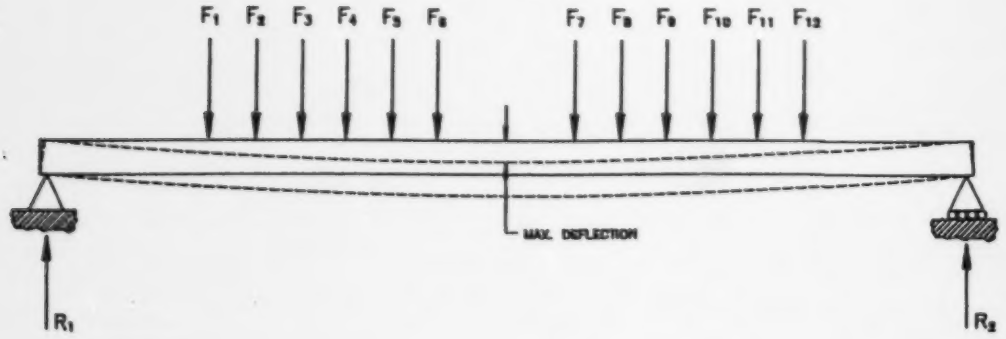


FIGURE No. 2

where, a1=12 in, P1=50,000 lb
a2=36 in, P2=50,000 lb
a3=60 in, P3=150,000 lb
a4=84 in, P4=150,000 lb
a5=108 in, P5=150,000 lb
a6=132 in, P6=150,000 ib

REACTION GIRDER ymax=0.604 in

MODIFIED WIC PIPE BENDING RIG 18 09 90

No. of JACKS/SIDE=	16.00	PIPE d=	36.00 in
JACK CAPACITY=	50.00 klb	PIPE t=	1.250 in
LENGTH OF PIPE=	480.00 in	Ixx=	20625 in^4
REACTION FORCE=	800.00 klb	YIELD S=	80000.00 psi

DETA X [ft]	QTY	POSITION [ft]	V [klb]	M [Min.lb]	TOTAL M [Min.lb]	STRESS [ksi]	ymax [in]
0.00	0.00	0.00	800.00	0.00	0.00	0.00	0.0000
1.00	0.00	1.00	800.00	9.60	9.60	8.38	0.0000
2.00	0.00	3.00	800.00	19.20	28.80	25.13	0.0000
2.00	0.00	5.00	800.00	19.20	48.00	41.89	0.0000
2.00	2.00	7.00	700.00	19.20	67.20	58.65	0.3750
2.00	2.00	9.00	600.00	16.80	84.00	73.31	0.4688
2.00	3.00	11.00	450.00	14.40	98.40	85.88	0.8287
2.00	3.00	13.00	300.00	10.80	109.20	95.30	0.9358
2.00	3.00	15.00	150.00	7.20	116.40	101.58	1.0211
2.00	3.00	17.00	0.00	3.60	120.00	104.73	1.0813
2.00	0.00	19.00	0.00	0.00	120.00	104.73	0.0000

r2=	18.000	in	4.7106
r1=	16.750	in	
K=	1.318	SHAPE FACTOR	
My=	91.667	Min.lb	
Mp=	120.808	Min.lb	

MODIFIED WIC PIPE BENDING RIG 18 09 90

No. of JACKS/SIDE=	16.00	PIPE d=	36.00 in
JACK CAPACITY=	26.10 Klb	PIPE t=	0.625 in
LENGTH OF PIPE=	480.00 in	Ixx=	10868 in 4
REACTION FORCE=	417.60 Klb	YIELD S=	80000.00 psi

DETA X [ft]	QTY	POSITION [ft]	V [Klb]	M [Min.lb]	TOTAL M [Min.lb]	STRESS [ksi]	ymax [in]
0.00	0.00	0.00	417.60	0.00	0.00	0.00	0.0000
1.00	0.00	1.00	417.60	5.01	5.01	8.30	0.0000
2.00	0.00	3.00	417.60	10.02	15.03	24.90	0.0000
2.00	0.00	5.00	417.60	10.02	25.06	41.50	0.0000
2.00	2.00	7.00	365.40	10.02	35.08	58.10	0.3715
2.00	2.00	9.00	313.20	8.77	43.85	72.62	0.4644
2.00	3.00	11.00	234.90	7.52	51.36	85.07	0.8209
2.00	3.00	13.00	156.60	5.64	57.00	94.41	0.9270
2.00	3.00	15.00	78.30	3.76	60.76	100.63	1.0115
2.00	3.00	17.00	0.00	1.88	62.64	103.74	1.0711
2.00	0.00	19.00	0.00	0.00	62.64	103.74	0.0000

4.6663

r2=	18.000	in
r1=	17.375	in
K=	1.295	SHAPE FACTOR
My=	48.304	Min.lb
Mp=	62.576	Min.lb

MODIFIED WIC PIPE BENDING RIG 11 10 90

No. of JACKS/SIDE=	20.00	PIPE d=	42.00 in
JACK CAPACITY=	50.00 Klb	PIPE t=	1.250 in
LENGTH OF PIPE=	480.00 in	Ixx=	33248 in^4
REACTION FORCE=	1000.00 Klb	YIELD S=	70000.00 psi

DETA X [ft]	QTY	POSITION [ft]	V [Klb]	M [Min.lb]	TOTAL M [Min.lb]	STRESS [ksi]	ymax [in]
0.00	0.00	0.00	1000.00	0.00	0.00	0.00	0.0000
1.00	0.00	1.00	1000.00	12.00	12.00	7.58	0.0000
2.00	0.00	3.00	1000.00	24.00	36.00	22.74	0.0000
2.00	0.00	5.00	1000.00	24.00	60.00	37.90	0.0000
2.00	3.00	7.00	850.00	24.00	84.00	53.06	0.3490
2.00	3.00	9.00	700.00	20.40	104.40	65.94	0.4362
2.00	3.00	11.00	550.00	16.80	121.20	76.55	0.5141
2.00	4.00	13.00	350.00	13.20	134.40	84.89	0.7740
2.00	4.00	15.00	150.00	8.40	142.80	90.20	0.8446
2.00	3.00	17.00	0.00	3.60	146.40	92.47	0.6708
2.00	0.00	19.00	0.00	0.00	146.40	92.47	0.0000
							3.5885

r2=	21.000 in	
r1=	19.750 in	
K=	1.311	SHAPE FACTOR
My=	110.826	Min.lb
Mp=	145.345	Min.lb

MODIFIED WIC PIPE BENDING RIG 11 10 90

No. of JACKS/SIDE=	24.00	PIPE d=	42.00 in
JACK CAPACITY=	50.00 Klb	PIPE t=	1.500 in
LENGTH OF PIPE=	480.00 in	Ixx=	39184 in^4
REACTION FORCE=	1200.00 Klb	YIELD S=	70000.00 psi

DETA X [ft]	QTY	POSITION [ft]	V [Klb]	M [Min.lb]	TOTAL M [Min.lb]	STRESS [ksi]	ymax [in]
0.00	0.00	0.00	1200.00	0.00	0.00	0.00	0.0000
1.00	0.00	1.00	1200.00	14.40	14.40	7.72	0.0000
2.00	0.00	3.00	1200.00	28.80	43.20	23.15	0.0000
2.00	0.00	5.00	1200.00	28.80	72.00	38.59	0.0000
2.00	4.00	7.00	1000.00	28.80	100.80	54.02	0.3948
2.00	4.00	9.00	800.00	24.00	124.80	66.88	0.4935
2.00	4.00	11.00	600.00	19.20	144.00	77.17	0.5816
2.00	4.00	13.00	400.00	14.40	158.40	84.89	0.6567
2.00	4.00	15.00	200.00	9.60	168.00	90.04	0.7166
2.00	4.00	17.00	0.00	4.80	172.80	92.61	0.7589
2.00	0.00	19.00	0.00	0.00	172.80	92.61	0.0000
							3.6020

r2=	21.000	in
r1=	19.500	in
K=	1.319	SHAPE FACTOR
My=	130.614	Min.lb
Mp=	172.305	Min.lb

VOLUME OF WATER NECESSARY TO PRESSURIZE TEST PIPE

P=1000 psi l=480 in
d=36 in r1=d/2-t
t=0.625 in r2=d/2
E=30E6 psi (Young's Modulus)
ΔVw/Vw=0.00444 @ 1000 psi Compressibility of water
u=0.25 Poisson's Ratio (steel)

S1=Pr/t hoop stress
S2=Pr/2t axial stress

e1=1/E(S1-uS2) hoop strain
e2=1/E(S2-uS1) axial strain

therefore,

e1=Pr/Et(1-u/2)
e1=1000*18/(30E6*0.625)*(1-0.25/2)=0.00084 in/in

e2=Pr/Et(1/2-u)
e2=1000*18/(30E6*0.625)*(1-0.25/2)=0.00024 in/in

Δr=e1*r1=0.00084(34.75/2)=0.014595 in
Δl=e2*l=0.00024(480)=0.1152 in

V1= Δr*pi*2r1*l=0.02919*(pi*34.75)*480=764.80 in^3

V2= Δl*pi*r1^2=0.1152*pi*17.375^2=109.26 in^3

ΔVw/Vw=0.00444 compressibility of water @ 1000 psi

ΔVw=0.000444*Vw

Vw=4/3*pi*r1^3+pi*r1^2*l=477212 in^3
V3= ΔVw=0.00444(477212)=2118.82 in^3

Vt=V1+V2+V3=764.8+109.26+2118.82=2992.88 in^3

Vt=10.79 Imperial gal
=12.96 U.S. gal
=49.04 liters

APPENDIX C

COST ANALYSIS

PRESSURE SOURCE AND CONTAINMENT SYSTEM

Preparation and welding of the hemispherical dished ends to the reaction plates.	$ 4,500.00
Hydraulic pressuring system 5 gpm 5000 psi pump Transfer barrier & accumulator - 15 gal capacity Hydraulic control circuitry electrics Servo valve & manifold Pressure Transducer Hoses, etc Piping to hydraulic jacking system	26,080.00
Jacking System - 12 new Enerpac 50T jacks 13 1/4 " stroke	16,200.00
Hardware	200.00
Subtotal	$46,980.00

MODIFICATION OF LOADING FRAME

Modifications to the saddles Stiffener installation Reaction plates Round bar & bar support	$ 8,140.00
Modification to girder Spacer plates Jack mounting plate Hardware	4,285.00
Swivel mounts for jacks	2,100.00
Safety trays and covers	5,065.35 *
Painting	1,850.00 *
Subtotal	$21,440.00

* Carried over from WIC figures.

ELECTRONIC CONTROL AND DATA ACQUISITION

Two channel PC controlled servo system complete with independent signal generation, transducer excitation, servocontrollers, pump controller, and computers.	$42,000.00
128 channel data acquisition system	13,500.00
Subtotal	$55,500.00

FEES - Professional, technical, and administrative

Design & Engineering	$ 4,500.00
Assembly of complete system	6,500.00
Supervision	2,500.00
Subtotal	$13,500.00
TOTAL	$137,420.35

FULL SCALE PRESSURIZED PIPE BUCKLING TEST

Welding Institute of Canada Proposal PC 412/1/1990
To
MDT Engineering

The cost estimates (based on DSS rates) for welding and strain gauging of a single pipe are the following:

(1) Welding of Test Pipe to Loading End Fixtures

The test pipe 36" in diameter X 0.75" in wall thickness welded in an alignment - welding jig outside the test rig. The test pipe will be girth welded to the 36" diameter X 0.75" wall pipes of the loading end fixtures.

	Labour	Hours	Cost, $
Cut, bevel, grind, align and prepare the groove for girth welding (2 girth weld grooves)	P4	8 H	601.60
	T3	40 H	2130.00
Preheat, weld and clean (2 girth welds)	P4	4 H	300.80
	T3	16 H	852.00
Consumables + gas	T3	2 H	106.50
	P4	1 H	75.20
			500.00
NDT	T3	2 H	106.50
	P4	1 H	75.20
			600.00

(2) Mounting Strain Gauges on the Outside Surface of the Pipe

The following will estimate the cost of mounting 100 strain gauges of the type EA-06-250BG-120.

Locate, grind and polish	P4	12 H	902.40
	T3	64 H	3408.00
Prepare 100 gauges for mounting	P4	4 H	300.80
	T3	20 H	1065.00
Machine spacers to protect gauges from the loading jacks	T3	8 H	426.00

Mount 100 strain gauges, solder lead wires, mount spacers and coat the gauges	P4	20 H	1504.00
	T3	100 H	5325.00
Prepare lead wires for the gauges	T3	16 H	852.00

Materials

Strain gauges (100) of the type EA-06-250BG-120			1300.00
	T3	2 H	106.50
Adhesives, tapes, slides, and coating			400.00
Grinding discs and polishing papers			250.00
	T3	1 H	53.25
Lead wires (3 spools) + solders			750.00
	T3	1 H	53.25
	P4	2 H	106.50
Total cost			**23100.00**

N.B. These estimates do not include the cost for loading the pipe to the test rig, connecting the leads to data acquisition system and full scale testing. Also, report preparation and girth welds made with special instructions using 2 to 4 welders would require separate costing.

Oakville, Ontario
September 21, 1990

Dr. U. Mohaupt
MDT Engineering Ltd.
550 Parkside Drive
Unit A 23
Waterloo, Ontario
N2L 5V4

Dear Udo:

Re: Full Scale Pressurized Pipe Buckling Test, WIC Proposal PC 412/1/1990

In addition to our previous estimates, the following are the cost estimates for trays and covers for the test rig, painting of the full scale test rig, loading the test specimen to the rig plus performing the test and shut down operations.

	Labour	Hours	Cost, $
A. SAFETY TRAYS AND COVERS			
Carbon steel sheet and welding consumables			2000.00
Plate bending			600.00
Welding and other services	T3	35 11	1863.75
	P4	8 11	601.60
TOTAL (A)			**5065.35**
B. PAINTING THE TEST RIG			
Cleaning, painting and paint materials (Contract)			1850.00
TOTAL (B)			**1850.00**

C. FULL SCALE TEST

(i) Remove the loading ends from the test rig and cut	T3	32 H	1704.00
	P4	8 H	601.60
(ii) Weld water filled inserts	T3	8 H	426.00
	P4	2 H	150.40
(iii) Load specimen to the rig	T3	32 H	1704.00
	P4	8 H	601.60
(iv) Connect jacks, attach hydraulic lines and connect wires	T3	16 H	852.00
	P4	8 H	601.60
(v) Testing	T3	16 H	852.00
	P4	8 H	601.60
(vi) Shut down, drain water, remove test piece from the rig	T3	40 H	2130.00
	P4	6 H	451.20
(vii) Cut test pipe out	T3	12 H	639.00
	P4	2 H	150.40
Materials: gas, electrodes and water			1400.00
TOTAL (C)			**12865.40**
TOTAL (A) + TOTAL (B) + TOTAL (C)		**$**	**19780.75**

Should you have any questions please contact me.

Sincerely,

Sathish Rao Bala, P.Eng.
Research Engineer
Materials Technology